Published in final edited form as:

J Learn Disabil. 2006 ; 39(1): 48–55.

Reading Skills in Early Readers: Genetic and Shared Environmental Influences

Stephen A. Petrill, Kirby Deater-Deckard, Lee Anne Thompson, Laura S. DeThorne, and Christopher Schatschneider

Abstract

The present study combined parallel data from the Northeast-Northwest Collaborative Adoption Projects (N2CAP) and the Western Reserve Reading Project (WRRP) to examine sibling similarity and quantitative genetic model estimates for measures of reading skills in 272 school-age sibling pairs from three family types (monozygotic twins, dizygotic twins, and unrelated adoptive siblings). The study included measures of letter and word identification, phonological awareness, phonological decoding, rapid automatized naming, and general cognitive ability. Estimates of additive genetic effects and shared environmental effects were moderate and significant. Furthermore, shared environmental effects estimated in twins were generally similar in magnitude to adoptive sibling correlations, suggesting highly replicable estimates across different study designs.

Previous research has convincingly demonstrated that genetics are important to familial resemblance in reading ability and disability (e.g., Harlaar, Spinath, Dale, & Plomin, 2005; Pennington & Smith, 1983; Stevenson, Graham, Fredman, & McLoughlin, 1987). Genetic influences are important not only to reading outcomes, but also to components of reading ability, such as phonological awareness, phonological decoding, reading comprehension, spelling, orthographic knowledge, and rapid automatized naming (see Compton, Davis, DeFries, Gayan, & Olson, 2001; Gayan & Olson, 2001, 2003; Knopik, Alarcón, & DeFries, 1998; Olson, Forsberg, & Wise, 1994; Olson, Gillis, Rack, DeFries, & Fulker, 1991). Furthermore, quantitative trait loci (QTLs) have been identified for reading on the short arms of Chromosomes 2,6,15, and 18 and have been replicated across independent laboratories (Cardon et al., 1994; Fagerheim et al., 1999; Fisher et al., 1999; Fisher et al., 2002; Gayan et al., 1999; Grigorenko et al., 1997; Grigorenko, Wood, Meyer, & Pauls, 2000).

In general, the aforementioned research on reading suggests that although there is some very modest evidence for shared environmental influences, genes are the primary force in shaping familial resemblance in reading skills. However, most of these behavioral genetic studies have examined twins of late elementary school age or older. In a recent study, Byrne et al. (2002) examined genetic and environmental influences on a large battery of reading measures in a sample of preschool-age, monozygotic (MZ) and same-sex dizygotic (DZ) twin pairs recruited in the United States (63 MZ, 79 DZ), Australia (46 MZ, 27 DZ), and Norway (16 MZ, 19 DZ). In all, 25 measures were used to form the following reading composites: Phonological Awareness and Synthesis, Phoneme Identity Training, Learning and Memory, Grammar and Morphology, Vocabulary, and Print Knowledge.

Unlike the studies of older children (e.g., Gayan & Olson, 2001, 2003), Byrne et al. (2002) found that shared environmental influences were moderate and significant for Grammar and

Morphology ($c^2 = .43$), Vocabulary ($c^2 = .49$), and Print Knowledge ($c^2 = .55$), whereas genetic effects were modest and usually not significant ($h^2 = .22, .18$, and $.28$, respectively). On the other hand, Byrne et al. found that genetic influences were similar to those found in older samples for Phonological Awareness ($h^2 = .52$), Phoneme Identity ($h^2 = .50$), and Learning and Memory ($h^2 = .47$), which demonstrated non-significant shared environmental effects ($c^2 = .16, .22$, and $.00$, respectively). Thus, from this first genetically sensitive study of preschool-age children, it appears that knowledge of grammar, vocabulary, and print is influenced by the shared family environment. In contrast, measures of learning and memory, phonemic awareness, and phoneme identity display genetic effects but not shared environmental effects, similar to results found when examining reading skills in older children.

However, Byrne et al. (2002) examined children in the United States, Australia, and Scandinavia. Differences in schooling and differences in the larger culture may have unknown implications for estimates of the shared environment. Thus, it is not known whether the evidence for shared environmental effects found by Byrne et al. are due to the age of the sample or due to the unique sampling strategy.

More generally, nearly all genetic studies on reading to date have involved twins, meaning that the power to detect shared environmental influences has been limited. Estimates of the shared environment in twin studies are essentially the residual of the familial resemblance that is not accounted for by MZ versus DZ twin similarity. In contrast, any similarity among genetically unrelated, adoptive family members is a *direct* test of the shared environment (to the extent that selective placement is not operating). To date, there has been only one published adoption study of reading, the Colorado Adoption Project (CAP). This study suggested significant genetic influences in reading at ages 7, 12, and 16 ($h^2 = .49$) but zero shared environmental influences (Wadsworth, Corley, Hewitt, Plomin, & DeFries, 2002).

In contrast, results are emerging from the new Northeast-Northwest Collaborative Adoption Projects (N2CAP; Deater-Deckard, Petrill, & Wilkerson, 2003) suggesting that individual measures of the adoptive reading environment (e.g., shared reading, parental involvement) are associated with adoptive children's reading outcomes (Petrill, Deater-Deckard, Schatschneider, & Davis, 2005). Moreover, parent-offspring analyses in N2CAP have shown that adoptive parent-offspring correlations are significant between parental cognitive/reading skills and children's phonemic awareness and letter identification (Petrill, Deater-Deckard, Schatschneider, & Davis, 2004), but only in younger readers. In general, these studies emerging from N2CAP indicate that the shared family environment may be important to reading, especially when examining phonological awareness and print knowledge in younger school-age children.

The present study combines participants from the Northeast-Northwest Collaborative Adoption Projects with twins from the Western Reserve Reading Project (WRRP) to examine the genetic and environmental influences on reading outcomes in a twin/adoption study of early elementary school-age children. Combining twin and adoption designs provides the most sensitive assessment of shared environmental effects and allows us to evaluate the generalizability of results across study designs. Given the results of Byrne et al. (2002), we expect that both genetic and shared environmental influences on reading-related outcomes will be moderate and significant, particularly with respect to reading outcomes such as expressive vocabulary and print knowledge.

Method

Participants

Western Reserve Reading Project—The Western Reserve Reading Project is an ongoing, 4-year longitudinal cohort sequential study examining gene-environment processes in the development of early reading and related cognitive skills. The vast majority of participating families live in the Greater Cleveland, Columbus, and Cincinnati metropolitan areas, with other families living throughout Ohio and Western Pennsylvania. Recruiting is conducted largely through school nominations ($n = 273$ schools, corresponding to more than 80% of enrolled families). Schools are asked to forward a packet of information to parents with twins who have entered kindergarten but not yet completed first grade. This packet includes a letter and brochure describing the study and a stamped return postcard of interest addressed to the project offices at the Pennsylvania State University. Parents who return the postcard are then contacted by telephone and, if interested, are sent a 5- to 10-min demographic questionnaire to obtain additional contact information, names and ages of the twins and other children living in the home, parent education, occupation, and ethnicity. Parents who return this packet are officially enrolled in the study. Additional families have been recruited via Ohio State birth records, mother of twin clubs, and media advertisement.

As part of the ongoing study, twins are assessed in their homes four times over a 3-year period. The current study examined the 102 monozygotic (MZ) twin pairs (61% female) and 140 dizygotic (DZ) same-sex twin pairs (53% female) who had completed the first home assessment. All children were in kindergarten or first grade. The mean age was 6.1 years ($SD = .74$, range = 5.0–7.9) for MZ twins and 6.1 years ($SD = .66$, range = 4.3–7.7) for DZ twins. Parent education levels varied widely and were very similar for mothers and fathers: 1%–2% high school or less, 39% some college, 30% bachelor's degree, 25% some postgraduate education or degree, 5% not specified. Most families were two-parent households (6% single mothers), and nearly all were White (92%).

Northeast-Northwest Collaborative Adoption Projects—The second study is the Northeast-Northwest Collaborative Adoption Projects (Deater-Deckard et al., 2003), a national volunteer sample of 241 adoptive families, composed of 354 children (55% female; age in years, $M = 7.9$, $SD = 2.5$, range = 4–13; age of placement, $M = 1.09$, $SD = 1.54$). Families were recruited through parent contact letters sent anonymously through private adoption agencies. Similar to the WRRP twin study, parents who returned a postcard of interest to the project office were then contacted and sent a demographic questionnaire. Those families who returned this questionnaire were enrolled in the study (see Deater-Deckard et al., 2003, for more information). Nearly all of the parents were married or cohabiting couples (88%) and were White (95%). Like other adoption study samples, the parents were highly educated; three quarters had a 4-year degree or higher. Most of the adopted children in these families (84%) were born outside the United States: Korea (36%), China (27%), other Asian countries (e.g., India, Vietnam; 11%), Eastern Europe (e.g., Romania, Bulgaria; 6%), and South and Central America (e.g., Guatemala, Mexico; 3%). A few were adopted from Africa. It is important to note that the N2CAP sample was not designed to be representative of internationally adopting parents in the United States. This distribution of birth countries instead represents the nations that work with the particular adoption agencies that helped recruit the participating families.

For the purposes of the current study, we selected families with two genetically unrelated siblings, one of whom was in the age range of the WRRP sample (5–7 years). To match the adoptive siblings as closely as possible to the WRRP twin sample, we further specified that the other sibling be between the ages of 4 and 10 years and of the same sex. This selection yielded 30 pairs of genetically unrelated same-sex siblings (57% female). Siblings were almost identical to the larger N2CAP sample on the outcome measures employed in the current study

(see Petrill et al., 2005, for descriptive information on the larger N2CAP sample). Compared to the twin study, the children in the adoption study spanned a broader age range and were one year older on average ($M = 7.3$, $SD = 1.72$, range = 4.0–9.9).

For all of the analyses of sibling similarity in the adoption study, we controlled statistically for age of placement and age of placement squared (regression residuals) in light of previous research indicating linear and nonlinear age of placement effects on mean levels of reading skills (Petrill & Deater-Deckard, 2004). In sum, the current study involved 102 pairs of MZ twins, 140 same-sex pairs of DZ twins, and 30 genetically unrelated same-sex siblings living in the same home.

Procedure and Measures

Children in both studies were assessed on a 90-min battery of cognitive and reading-related outcome measures as part of a larger home visit protocol. Separate testers assessed each child in separate rooms. The following measures were collected in both studies:

1. *General cognitive ability* (g) was assessed through a short form of the *Stanford-Binet Intelligence Scale* (Thorndike, Hagen, & Sattler, 1986), which included the Vocabulary, Pattern Analysis, Memory for Sentences, Memory for Digits, and Quantitative subtests;
2. *Letter knowledge, word identification, and phonological decoding* were evaluated using the *Woodcock Reading Mastery Test–Revised* (WRMT-R; Woodcock, 1987) Letter Identification, Word Identification, and Word Attack subtests, respectively; and
3. *Phonological awareness* was assessed using six subtests from Robertson and Salter's (1997) *Phonological Awareness Test* (PAT), which included assessments of rhyming (discrimination and production), phoneme isolation (initial), phonemic segmentation (whole word), and phonemic deletion (syllabic deletion and phoneme deletion). Given that phonological awareness has arguably been shown to be a unitary construct (Schatschneider, Francis, Foorman, Fletcher, & Mehta, 1999), the six PAT subtests were summed to form a general raw score for phonological awareness. This raw score was then residualized for child age and gender using a regression procedure for further analysis.

In addition to the shared measures across WRRP and N2CAP, the WRRP twin study assessed *rapid automatized naming* using the Letter Naming and Number Naming tasks from the *Comprehensive Test of Phonological Processing* (Wagner, Torgesen, & Rashotte, 1999). The Letter and Number Naming subtests were highly correlated ($r = .73$) and, thus, were z-scored, summed, and residualized on child age and gender to form a Rapid Automatized Naming composite score.

Results

Descriptive statistics and sibling intra-class correlations are shown in Table 1. Average psychometric scores were slightly negatively skewed from the age-normed mean of 100, and the variances were slightly restricted by the age-normed standard deviation of 15. Descriptively examining the intraclass correlations, sibling similarity was greatest between MZ twins (.72–.91), intermediate for DZ twins (.54–.66), and lowest between genetically unrelated adoptive siblings for all measures (.22–.32, with $-.17$ for g being a noticeable exception to the general pattern of positive correlations). Overall, increased similarity based on the degree of genetic relatedness suggests additive genetic influences. Shared environmental influences are also indicated by the following findings: (a) Identical twins are generally less than 2 times more

similar than fraternal twins, and (b) adoptive sibling correlations are significantly different from zero for phonological awareness and word attack.

To quantify and test the significance of these genetic and environmental influences, we employed univariate ACE structural equation models based on raw data (A = additive genetic variance; C = shared environmental variance; E = nonshared environmental variance, including measurement error; Neale & Cardon, 1992) using *Mx* (Neale, Boker, Xie, & Maes, 1999). In essence, this model tests whether the covariance between siblings is moderated by their degree of genetic relatedness. The variance/covariance between MZ twins is parameterized as follows:

	Twin1	Twin2
Twin1	A+C+E	A+C
Twin2	A+C	A+C+E

Twin 1's and Twin 2's variances are hypothesized to be a function of additive genetic (A), shared environmental (C), and unshared environmental (E) influences. The covariance between Twin 1 and Twin 2 is $A + C$, because identical twins share 100% of the same genes and, by definition, 100% of the shared environment. For DZ twins, the variance is the same as for MZ twins ($A + C + E$), but the covariance between DZ twins is parameterized as $0.5A + C$, because fraternal twins share 50% of the same genes and 100% of the shared environment. The variance for adoptive siblings is also $A + C + E$, but the covariance between unrelated adoptive siblings is C , because adoptive siblings share no genes but 100% of the shared environment. Put another way, to the extent that identical twins are more similar than fraternal twins, who are more similar than adoptive siblings, the contribution of genetics (A) will be significant. To the extent that identical twins, fraternal twins, and adoptive siblings are similarly correlated, the contribution of the shared environment (C) will be significant. To the extent that identical twins are correlated less than $r = 1.0$, the contribution of the nonshared environment (E) will be significant.

Similar to the logic of multiple regression or confirmatory factor analysis, ACE models are generally used to test the hypothesis that genetics (A), shared environment (C), and non-shared environment/error (E) are significantly different from zero, as assessed by 95% confidence intervals. Like all inferential statistics, this methodology has less power to detect differences in point estimates across measures (e.g., testing the hypothesis that the difference in heritability between phonological awareness and rapid automatized naming is different from zero). Thus, we employed ACE models to test whether the pattern of significance varied across reading-related outcomes.

Because of sample size differences between the twin and adoption samples, we first conducted a series of ACE models using twin data only, one model for each variable (see Table 2). Heritability estimates were moderate to large in magnitude, ranging from $h^2 = .22$ for letter identification to $h^2 = .77$ for rapid automatized naming. Shared environmental influences ranged from $c^2 = .01$ for rapid automatized naming to $c^2 = .50$ for letter identification. Notably, both genetic and environmental influences were moderate and significant for g, word attack, and phonological awareness.

Next, we employed the same univariate modeling strategy, but included twins and adoptive siblings in the same model for all variables, with the exception of rapid automatized naming (which was not collected in the adoption study). These results are also presented in Table 2. The estimates were similar in magnitude to those based on the twin data only; however, with the addition of the adoptive data, genetic and environmental influences were moderate and

statistically significant for letter identification as well as the previously significant estimates for g , word identification, and phonological decoding. It is important to note that this high degree of similarity between twin-only and combined adoption/twin model fitting results may be driven by the overrepresentation of twins in the analyses as well as by the similarity in results across twin and adoptive samples.

Finally, because reading performance is associated with general cognitive ability, reading scores were residualized for g using a multiple regression procedure. These residualized scores were then subjected to the same ACE modeling procedures (see Table 3). Point estimates for the residualized scores were highly similar to those found for the unadjusted scores (see Table 2) and were well within the 95% confidence intervals of the estimates. The only exception was the genetic estimate for letter identification in the twin-only analyses, where $h^2 = .05$ for the g residualized score and $h^2 = .22$ for the unadjusted score. However, neither estimate was significantly different from zero.

Discussion

The data presented in this brief report provided a systematic test of the genetic and environmental sources of variance in reading skills among children in kindergarten and first grade. Multiple measures of reading-related outcomes were employed; in the case of g , phonological awareness, and rapid automatized naming, multiple measures were employed to form composite measures. In contrast to previous studies of older children, shared environmental influences were significant and substantial, accounting for one third to one half of the variance for g , letter identification, phonological decoding, and phonological awareness. In contrast, familial resemblance for rapid automatized naming was influenced almost completely by genetic variance.

In particular, the c^2 estimates derived from the twin-only models (see Table 2) were mirrored by the adoptive sibling intraclass correlations (see Table 1). Although they provide a direct test of the shared environment, adoptive siblings have many potential differences that might attenuate the magnitude of their correlations. The 30 adoptive sibling pairs participating in this study were generally from the same countries, but children from these 30 families were born in many different countries, each with important differences in age of placement, quality of the preadoptive environment, and exposure to English language sounds. Despite these differences, adoptive intraclass correlations were significantly different from zero for phonological awareness and word attack, and nonsignificant trends were found for letter identification and word identification. More important, with the exception of g , the adoptive sibling intra-class correlations (our only direct test of shared environmental variance) were very similar to the estimates of shared environmental variance derived from the modeling of the twin data (see Table 2). Taken together, these results suggested significant shared environmental influences that were generally consistent across twin and adoption designs.

Thus, similar to Byrne et al. (2002), the evidence for significant shared environmental influences in the current study depended on the type of reading measure—with content-based reading measures (e.g., letter identification) more likely to show shared environmental influence than process-based measures of reading (e.g., rapid automatized naming). However, unlike Byrne et al. (2002), we found significant and substantial shared environmental influences for phonological awareness and decoding. These findings suggest that c^2 accounts for 30% to 40% of the individual differences in phonological skills, whereas Byrne et al. (2002) found that c^2 accounted for 15% to 25%. These differences may be explained by sampling differences between the two studies; as mentioned earlier, Byrne et al.'s sample was composed of children from the United States, Australia, and Scandinavia, whereas the samples for the current study were composed of twin pairs recruited in the midwestern United States

and domestically and internationally adopted children living in the Pacific Northwest and New England. However, it is important to note that the point estimates of shared environmental influence in Byrne et al.'s study, though nonsignificant, were not zero. Thus, the variability in results may be due to normal variance in the sampling distribution of the population of children who are learning to read.

More generally, as noted in the results section, the behavioral genetic method possesses much greater power to detect whether h^2 , c^2 , and e^2 estimates are significantly different from zero—as opposed to detecting whether these estimates are different from *each other*. This was evidenced in the confidence intervals presented in the current study, which were different from zero in most cases but generally overlapped with one another.

Nevertheless, the current study suggests a pattern of statistically significant shared environmental influences that is largely consistent with the results of Byrne et al. (2002) and is different from the findings of studies examining older children (e.g., Gayan & Olson, 2003). Although not explicitly tested, the data in the current study and in Byrne et al. (2002) are consistent with a developmental shift in the etiology of individual differences in reading skills in the early school years, particularly for content-based reading skills. When examining other cognitive skills, such as general cognitive ability, researchers have found a consistent trend where genetic and shared environmental influences are both moderate ($h^2 = .30-.40$) in younger children. In middle childhood, h^2 begins to get larger at the expense of c^2 . By adolescence, h^2 approaches .60 to .80, and shared environmental variance approaches zero (see McGue, Bouchard, Iacono, & Lykken, 1993). This trend is found whether looking at different children at different ages (Petrill, 2003) or at the same children as they age (Plomin, Fulker, Corley, & DeFries, 1997).

Research examining the development of reading skills has emphasized the distinction between young children who are “learning to read,” as opposed to older children who are “reading to learn.” For example, Chall (1983) argued that young children who are learning to read are primarily tasked with learning to read words that already are present in their oral vocabulary. The main requirements of successfully learning to read at this stage are phonological awareness, orthography, and visual-analytic ability (see Dale & Crain-Thoreson, 1999). As reading skills mature, children are able to use reading to learn new words and to integrate these words into their developing semantic knowledge. Therefore, it is sensible that shared environmental influences would be greater for outcomes that are more likely to be influenced by direct instruction in the home, such as expressive vocabulary or print knowledge, as opposed to outcomes such as rapid automatized naming.

Moreover, research examining the environmental predictors of early literacy has suggested that reading-related knowledge and skills that children acquire in the home environment are associated with early reading success (McCardle, Scarborough, & Catts, 2001), but that the indices of the home environment that are important in young readers are no longer influential among older readers (Scarborough & Dobrich, 1994). It is also clear that phonological and print-letter skills become less important to later reading achievement, in favor of comprehension skills (e.g., Curtis, 1980). Thus, we should not be surprised that the shared environment is significant in these measures among children learning to read but is modest or negligible among older readers.

Taken together, these findings suggest that individual differences in early reading may be a function both of genetic differences in early readers and of familial differences in parent-driven, shared environmental influences, such as book sharing, parental verbal skills, and parental educational attitudes. As children learn to read, genetically mediated, child-driven influences may emerge that affect the probability of coming into contact with experiences associated with

positive or negative reading outcomes. Some examples of these experiences may be children's enjoyment of reading, children's desire to read on their own, and teachers' responses to children based on their reading skills. In previous studies and in this study, we have found that the shared environment is important in early reading when examining sibling correlation data, parent-offspring data, and the links between measured environments and child reading outcomes. As longitudinal data in the Western Reserve Reading Project become available, we will be able to answer two additional questions: To what extent do genes and environments influence the stability or instability of reading skills over time? and, to what extent do measured environmental influences on early reading shift from a shared environmental to a genetic etiology as children learn to read and as the environments associated with reading become more a function of their own reading skills?

Acknowledgements

N2CAP was supported by a grant from the Society for the Psychological Study of Social Issues, the Kathryn Rudolph Memorial Research Fund of the University of Oregon, and National Science Foundation grants (BCS-9907860, BCS-9907811, and BCS-0196511). WRRP was supported by NICHD grant HD38075 and NICHD/OSERS grant HD46167.

References

- Byrne B, Delaland C, Fielding-Barnsley R, Quain P, Samuelsson S, Høien T, et al. Longitudinal twin study of early reading development in three countries: Preliminary results. *Annals of Dyslexia* 2002;52:49–74.
- Cardon LR, DeFries JC, Fulker DW, Kimberling WJ, Pennington BF, Smith SD. Quantitative trait locus for reading disability on chromosome 6. *Science* 1994;265:276–279. [PubMed: 7939663]
- Chall, JS. Stages of reading development. New York: McGraw-Hill; 1983.
- Compton, DL.; Davis, CJ.; DeFries, JC.; Gayan, J.; Olson, RK. Genetic and environmental influences on reading and RAN: An overview of results from the Colorado Twin Study. In: Wolf, M., editor. Conference proceedings of the Dyslexia Research Foundation Conference in Extra-ordinary Brain Series: Time, fluency, and developmental dyslexia; Baltimore: York Press; 2001. p. 277-303.
- Curtis ME. Development of components of reading skill. *Journal of Educational Psychology* 1980;72:656–669.
- Dale PS, Crain-Thoreson C. Language and literacy in a developmental perspective. *Journal of Behavioral Education* 1999;9(1):23–33.
- Deater-Deckard, K.; Petrill, SA.; Wilkerson, B. The Northeast-Northwest Collaborative Adoption Project: Identifying family environmental influences on cognitive and social development. In: Deater-Deckard, K.; Petrill, SA., editors. Gene-environment processes in social behaviors and relationships. Binghamton, NY: Haworth; 2003. p. 157-178.
- Fagerheim T, Raeymaekers P, Tonnessen FE, Pedersen M, Tranebjaerg L, Lubs HA. A new gene (DYX3) for dyslexia is located on chromosome 2. *Journal of Medical Genetics* 1999;36:664–669. [PubMed: 10507721]
- Fisher SE, Francks C, Marlow AJ, MacPhie IL, Newbury DF, Cardon LR, et al. Independent genome-wide scans identify a chromosome 18 quantitative-trait locus influencing dyslexia. *Nature Genetics* 2002;30:86–91. [PubMed: 11743577]
- Fisher SE, Marlow AJ, Lamb J, Maestrini E, Williams DF, Richardson AJ, et al. A quantitative-trait locus on chromosome 6p influences different aspects of developmental dyslexia. *American Journal of Human Genetics* 1999;64:146–156. [PubMed: 9915953]
- Gayan J, Olson RK. Genetic and environmental influences on orthographic and phonological skills in children with reading disabilities. *Developmental Neuropsychology* 2001;20:487–511.
- Gayan J, Olson RK. Genetic and environmental influences on individual differences in printed word recognition. *Journal of Experimental Child Psychology* 2003;84:97–123. [PubMed: 12609495]

- Gayan J, Smith SD, Cherny SS, Cardon LR, Fulker DW, Brower AM, et al. Quantitative-trait locus for specific language and reading deficits on chromosome 6p. *American Journal of Human Genetics* 1999;64:157–164. [PubMed: 9915954]
- Grigorenko EL, Wood FB, Meyer MS, Hart LA, Speed WC, Shuster A, et al. Susceptibility loci for distinct components of developmental dyslexia on chromosome 6 and 15. *American Journal of Human Genetics* 1997;60:27–39. [PubMed: 8981944]
- Grigorenko EL, Wood FB, Meyer MS, Pauls DL. Chromosome 6p influences on different dyslexia-related cognitive processes: Further confirmation. *American Journal of Human Genetics* 2000;66:715–723. [PubMed: 10677331]
- Harlaar N, Spinath FM, Dale PS, Plomin R. Genetic influences on word recognition abilities and disabilities: A study of 7 year old twins. *Journal of Child Psychology and Psychiatry and Allied Disciplines* 2005;46(4):373–384.
- Knopik VS, Alarcón M, DeFries JC. Common and specific gender influences on individual differences in reading performance: A twin study. *Personality and Individual Differences* 1998;25:269–277.
- McCardle P, Scarborough HS, Catts HW. Predicting, explaining, and preventing children's reading difficulties. *Learning Disabilities Research & Practice* 2001;16:230–239.
- McGue, M.; Bouchard, TJ., Jr; Iacono, WG.; Lykken, DT. Behavioral genetics of cognitive ability: A lifespan perspective. In: Plomin, R.; McClearn, GE., editors. *Nature, nurture, and psychology*. Washington, DC: American Psychological Association; 1993. p. 59-76.
- Neale, MC.; Boker, SM.; Xie, G.; Maes, HH. *Mx: Statistical modeling*. Vol. 5. Richmond, VA: Department of Psychiatry, Medical College of Virginia; 1999.
- Neale, M.; Cardon, LR. *Methodology for genetic studies of twins and families*. Dordrecht, the Netherlands: Kluwer; 1992.
- Olson, RK.; Forsberg, H.; Wise, B. Genes, environment, and the development of orthographic skills. In: Berninger, VW., editor. *The varieties of orthographic knowledge I: Theoretical and developmental issues*. Dordrecht, the Netherlands: Kluwer; 1994. p. 27-71.
- Olson RK, Gillis JJ, Rack JP, DeFries JC, Fulker DW. Confirmatory factor analysis of word recognition and process measures in the Colorado Reading Project. *Reading and Writing* 1991;3:235–248.
- Pennington BF, Smith SD. Genetic influences on learning disabilities and speech and language disorders. *Child Development* 1983;54:369–387. [PubMed: 6347551]
- Petrill, SA. The development of intelligence: Behavioral genetic approaches. In: Sternberg, R.; Lautrey, J.; Lubart, T., editors. *Models of intelligence for the next millennium*. Washington, DC: American Psychological Association; 2003. p. 81-89.
- Petrill SA, Deater-Deckard K. The heritability of general cognitive ability: A within family adoption design. *Intelligence* 2004;32:403–409.
- Petrill, SA.; Deater-Deckard, K.; Schatschneider, C.; Davis, C. The Northeast–Northwest Collaborative Adoption Projects. 2004. Shared environmental influences on early reading and low reading performance. Manuscript submitted for publication
- Petrill SA, Deater-Deckard K, Schatschneider C, Davis C. Measured environmental influences on early reading: Evidence from an adoption study. *Scientific Studies of Reading* 2005;9(3):237–260.
- Plomin R, Fulker DW, Corley R, De-Fries JC. Nature, nurture, and cognitive development from 1 to 16 years. *Psychological Science* 1997;8:442–447.
- Robertson, C.; Salter, W. *The phonological awareness test*. East Moline, IL: LinguiSystems; 1997.
- Scarborough HS, Dobrich W. On the efficacy of reading to preschoolers. *Developmental Review* 1994;14:245–302.
- Schatschneider C, Francis DJ, Foorman BF, Fletcher JM, Mehta P. The dimensionality of phonological awareness: An application of item response theory. *Journal of Educational Psychology* 1999;91:467–478.
- Stevenson J, Graham P, Fredman G, McLoughlin V. A twin study of genetic influences on reading and spelling ability and disability. *Journal of Child Psychology and Psychiatry and Allied Disciplines* 1987;28:229–247.
- Thorndike, RL.; Hagen, EP.; Sattler, JM. *Guide for administering and scoring the fourth edition: Stanford-Binet Intelligence Scale*. Chicago: Riverside; 1986.

Wagner, RK.; Torgesen, JK.; Rashotte, CA. Comprehensive test of phonological processing. Austin, TX: PRO-ED; 1999.

Wadsworth SJ, Corley RP, Hewitt JK, Plomin R, DeFries JC. Parent-offspring resemblance for reading performance at 7, 12 and 16 years of age in the Colorado Adoption Project. *Journal of Child Psychology and Psychiatry and Allied Disciplines* 2002;43:769–774.

Woodcock, R. Woodcock reading mastery tests–Revised. Circle Pines, MN: American Guidance Service; 1987.

Biographies

Stephen A. Petrill, PhD, is an associate professor of biobehavioral health and the assistant director of the Center for Developmental and Health Genetics at Pennsylvania State University. His current interests involve examining gene-environment processes on the development of reading and math skills.

Kirby Deater-Deckard, PhD, is an associate professor of psychology at the University of Oregon. His research interests involve gene-environment processes on parenting and child social-emotional development.

Lee Anne Thompson, PhD, is an associate professor of psychology at Case Western Reserve University. Her interests involve the quantitative and molecular genetic study of cognitive ability, academic achievement, and temperament.

Laura S. De-Thorne, PhD, is an assistant professor of speech and hearing science at University of Illinois, Champaign-Urbana. Her research examines gene-environment processes on the development of spontaneous language skills and their relationship to reading outcomes.

Christopher Schatschneider, PhD, is an associate professor of psychology at Florida State University. His research interests involve educational psychology, learning disabilities, quantitative methods, and reading and language comprehension.

TABLE 1
Descriptive Statistics and Sibling Intraclass Correlations by Group

Measure	MZ		DZ		Ad		Sibling Intraclass <i>r</i>	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	MZ	DZ
<i>g</i>	101.7	13.6	101.1	12.3	101.2	15.4	.75*	.54*
Letter Identification	102.7	9.0	102.3	8.7	99.1	14.3	.72*	.60*
Word Identification	103.1	17.5	105.6	18.9	104.9	17.1	.89*	.55*
Word Attack	103.2	12.7	104.0	11.9	102.2	16.3	.82*	.54*
Phonological Awareness	36.6	13.2	35.8	12.9	36.4	17.3	.91*	.66*
Reading Comprehension	100.5	14.8	95.7	13.8	—	—	.80*	.54*
Rapid Automated Naming	84.1	31.7	85.5	36.0	—	—	.78*	.54*

Note. *g* = general cognitive ability; MZ = monozygotic twins; DZ = dizygotic twins; Ad = genetically unrelated adoptive siblings. Phonological Awareness is expressed in number of correct items (total possible correct for 6 subtests, 10 items each = 60), whereas Rapid Automated Naming is expressed in number of seconds to complete both Letter and Number Naming subtests. Both composites were residualized for age and gender prior to biometric analyses.

* $p < .05$.

TABLE 2
ACE Model Fit and Parameter Estimates for Twin-Only and Combined Adoptive and Twin Data Sets: Unadjusted Scores

Variable	h^2	95% CI	c^2	95% CI	e^2	95% CI	-2log likelihood	df
Models Based on Twin Data Only								
g	.30*	.05-.57	.42*	.17-.63	.28*	.21-.38	1203.57	461
Letter Identification	.22	.00-.47	.50*	.27-.69	.28*	.21-.39	1160.30	453
Word Identification	.68*	.48-.91	.22	.00-.42	.10*	.07-.14	1081.19	445
Word Attack	.49*	.26-.76	.31*	.05-.51	.20*	.15-.27	1143.66	449
Phonological Awareness	.48*	.33-.68	.43*	.23-.58	.09*	.07-.12	1092.36	470
Rapid Automatized Naming	.77*	.49-.84	.01	.00-.26	.22*	.16-.31	1205.63	450
Models Based on Twin and Adoption Data								
g	.44*	.22-.70	.29*	.04-.48	.27*	.20-.36	1361.14	514
Letter Identification	.35*	.17-.56	.39*	.20-.54	.26*	.20-.35	1327.83	504
Word Identification	.68*	.49-.90	.22	.00-.40	.10*	.07-.14	1206.25	489
Word Attack	.48*	.27-.72	.32*	.09-.51	.20*	.14-.27	1272.83	492
Phonological Awareness	.52*	.39-.68	.39*	.23-.53	.08*	.06-.11	1273.58	522

Note. h^2 = heritability; CI = confidence interval; c^2 = shared environmental variance; e^2 = nonshared environmental variance; g = general cognitive ability.

* $p < .05$.

TABLE 3
ACE Model Fit and Parameter Estimates for Twin-Only and Combined Adoptive and Twin Data Sets: Unadjusted Scores

Variable	h^2	95% CI	e^2	95% CI	e^2	95% CI	-2log likelihood	df
Models Based on Twin Data Only								
Letter Identification	.05	.00-.33	.57*	.33-.68	.38*	.28-.48	1185.99	453
Word Identification	.67*	.44-.88	.18	.00-.40	.15*	.11-.20	1120.28	445
Word Attack	.42*	.15-.72	.30*	.03-.53	.28*	.21-.38	1181.35	449
Phonological Awareness	.30*	.09-.52	.50*	.29-.66	.20*	.15-.29	1149.65	459
Rapid Automatized Naming	.72*	.43-.83	.04	.00-.29	.24*	.17-.33	1186.30	440
Models Based on Twin and Adoption Data								
Letter Identification	.25*	.06-.47	.41*	.21-.56	.34*	.26-.44	1352.86	502
Word Identification	.69*	.47-.88	.16	.00-.37	.15*	.11-.21	1233.27	487
Word Attack	.46*	.20-.74	.26*	.01-.48	.28*	.21-.27	1304.63	490
Phonological Awareness	.46*	.29-.66	.35*	.16-.51	.19*	.14-.25	1322.31	508

Note. h^2 = heritability; CI = confidence interval; c^2 = shared environmental variance; e^2 = nonshared environmental variance.

* $p < .05$.